Conductor Development Program Status

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Aug 5, 2003

Presentation Outline

- HEP Conductor Development Status

  --Jc improvements

  --$D_{effective}$

  --Fabrication issues

- Conductor Development Plans

  --Performance improvements

  --Cost reductions

  --New conductors

Goals and Target Specifications have been developed in collaboration with the CDG

- Goal: Provide <u>cost-effective</u>, <u>high-performance</u> superconductor required for luminosity upgrades and for the next generation high-energy physics colliders.

- Target specifications for the HEP conductor include:

--Jc (noncopper,12T,4.2 K): 3000 A/mm^2

--Effective filament size: 40 microns or less

--Piece length: Greater than 10,000 m in
                           wire diam. of 0.3-1.0 mm

--Heat treatment times: Less than 200 hr; target is
                           50 hr for wind and react

--Wire cost: Less than $1.50/kA-m (12 T,4.2 K)

Steps toward improvements in Jc

1. Optimize use of available space

   --OST and OKAS focus during first 2 years R&D

   --a Jc increase from 2000 to 3000 A/mm^2 (12 T, 4.2 K) has been achieved
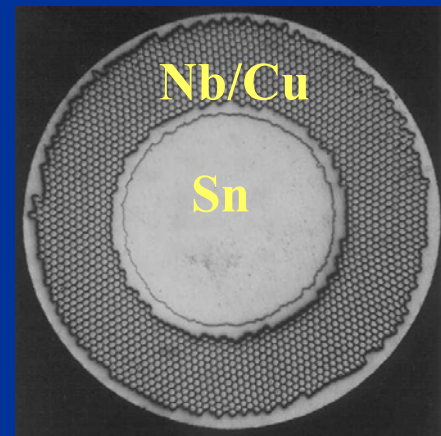
2. Optimize heat treatment

   --high Nb, Sn composites require different heat treatments (OST-MJR Jc increased from 2600 to 2900 A/mm^2)

   --Lab/Univ support includes microstructure evolution studies and improved Ic testing
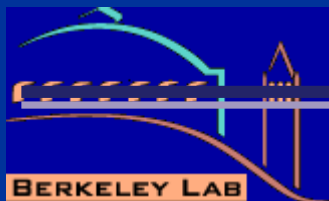
3. Refine grain size in Nb$_3$Sn

Nb/Cu

Sn

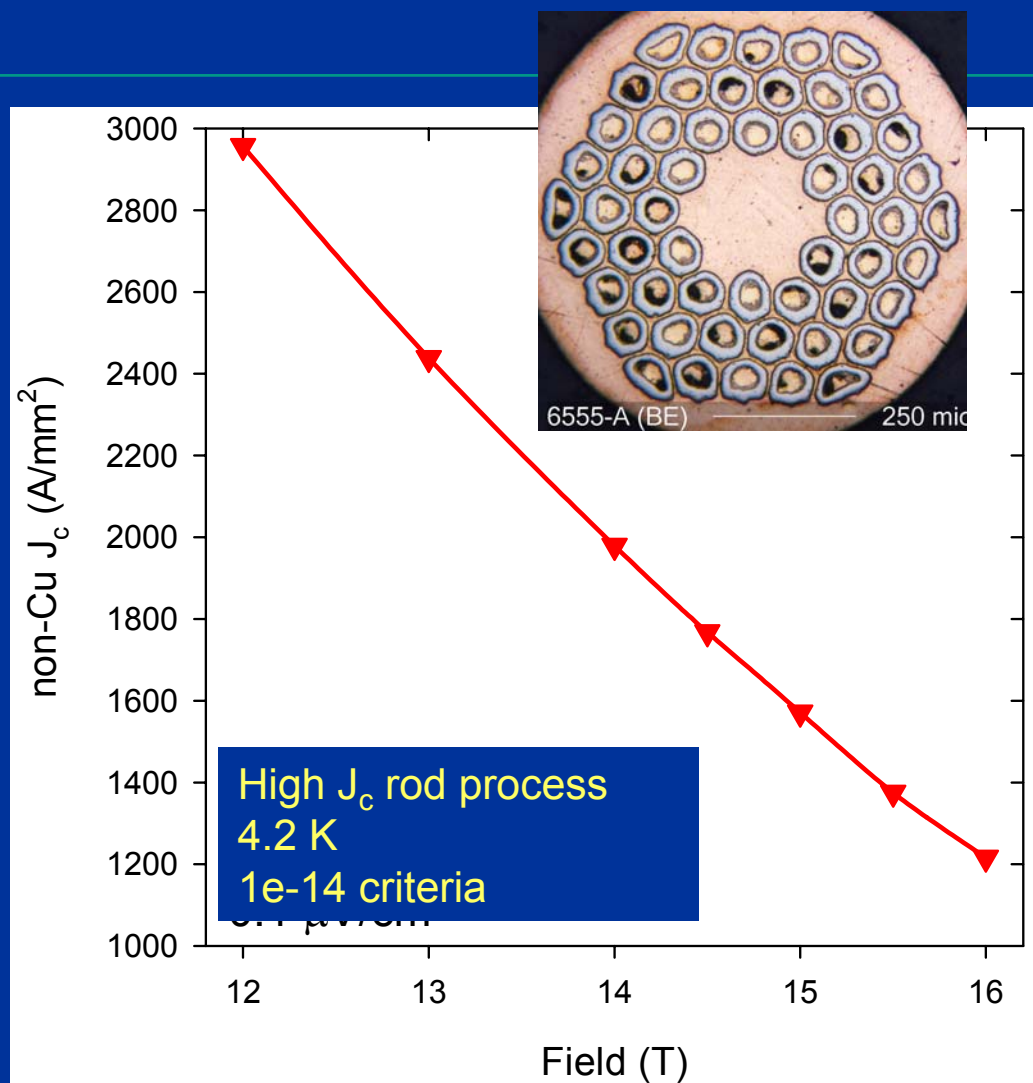# OST has achieved world record Jc values for Nb₃Sn made by two processes (LTSW Nov'02)
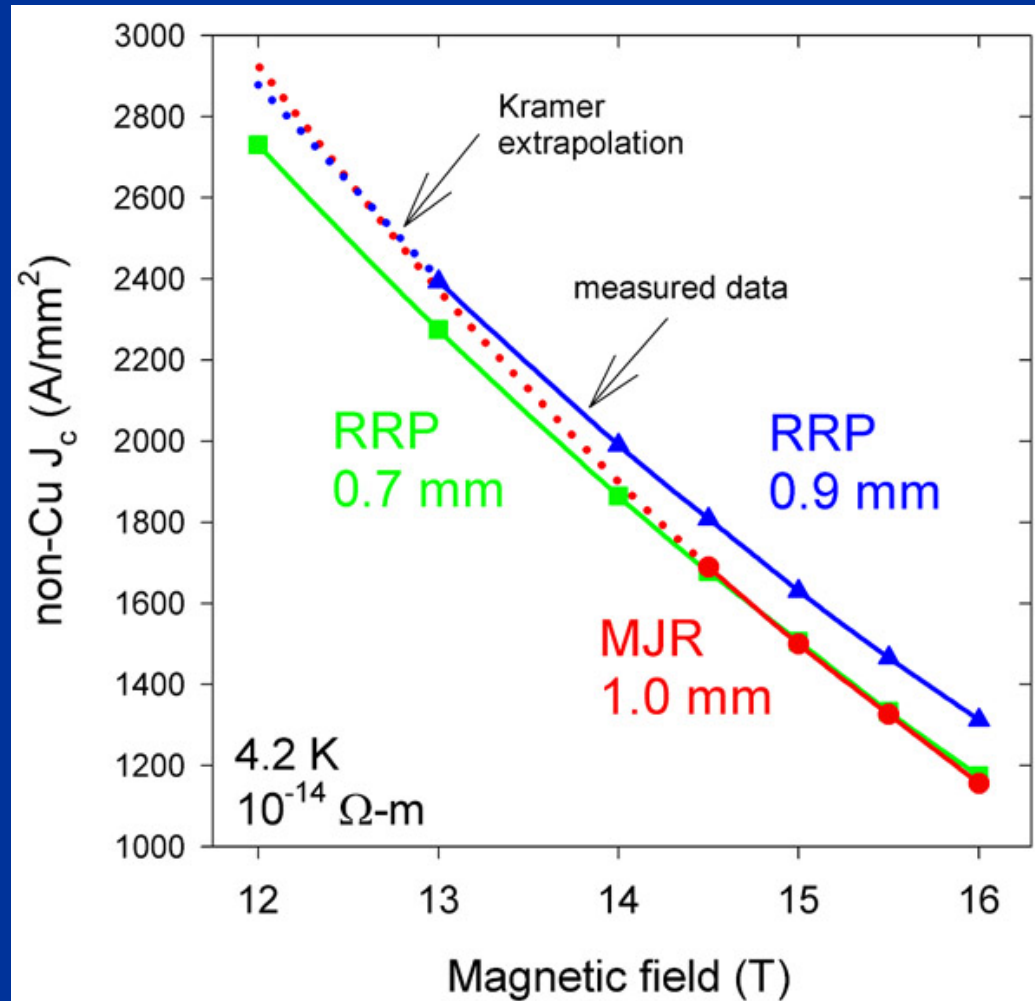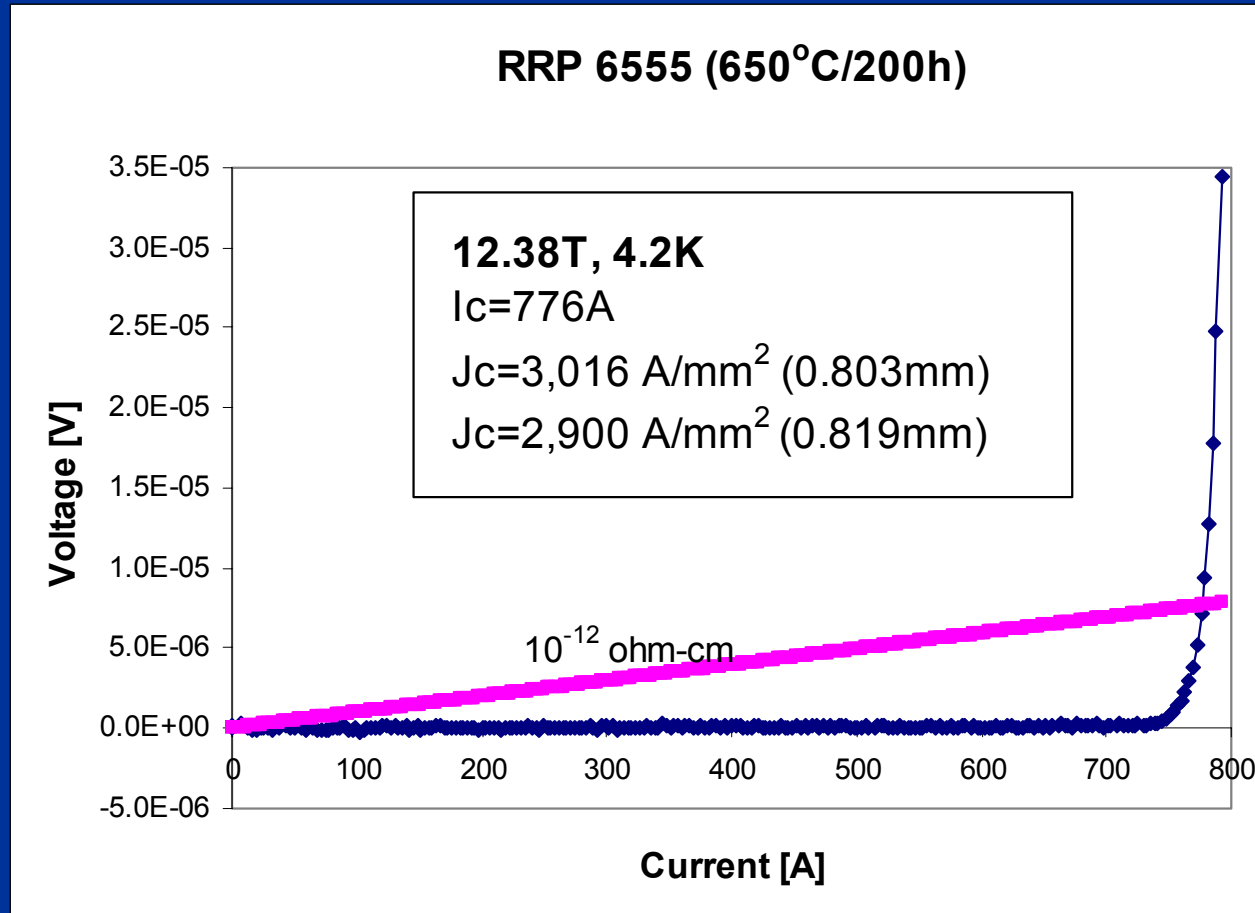
Rod process has replaced MJR at OST

- J_c performance as good or better than MJR

- Much better piece length than MJR

- Use of rods and extrusion instead of sheets and all-cold drawing makes yield more predictable

- J_c (12 T, 4.2)
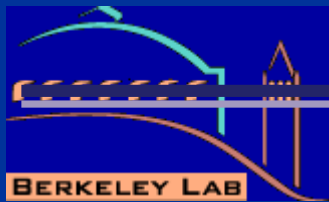   ~3000 A/mm² (one short sample over 3000 A/mm² at OST)

6555-A (BE)   250 mic

High J_c rod process
4.2 K
1e-14 criteria

non-Cu J_c (A/mm²) vs Field (T)

OST RRP Sample--HT and Test at LBNL

RRP 6555 (650°C/200h)

Graph labeled "Voltage [V]" on the y-axis (from -5.0E-06 to 3.5E-05) versus "Current [A]" on the x-axis (from 0 to 800).

Text box on graph:

12.38T, 4.2K
Ic=776A
Jc=3,016 A/mm^2 (0.803mm)
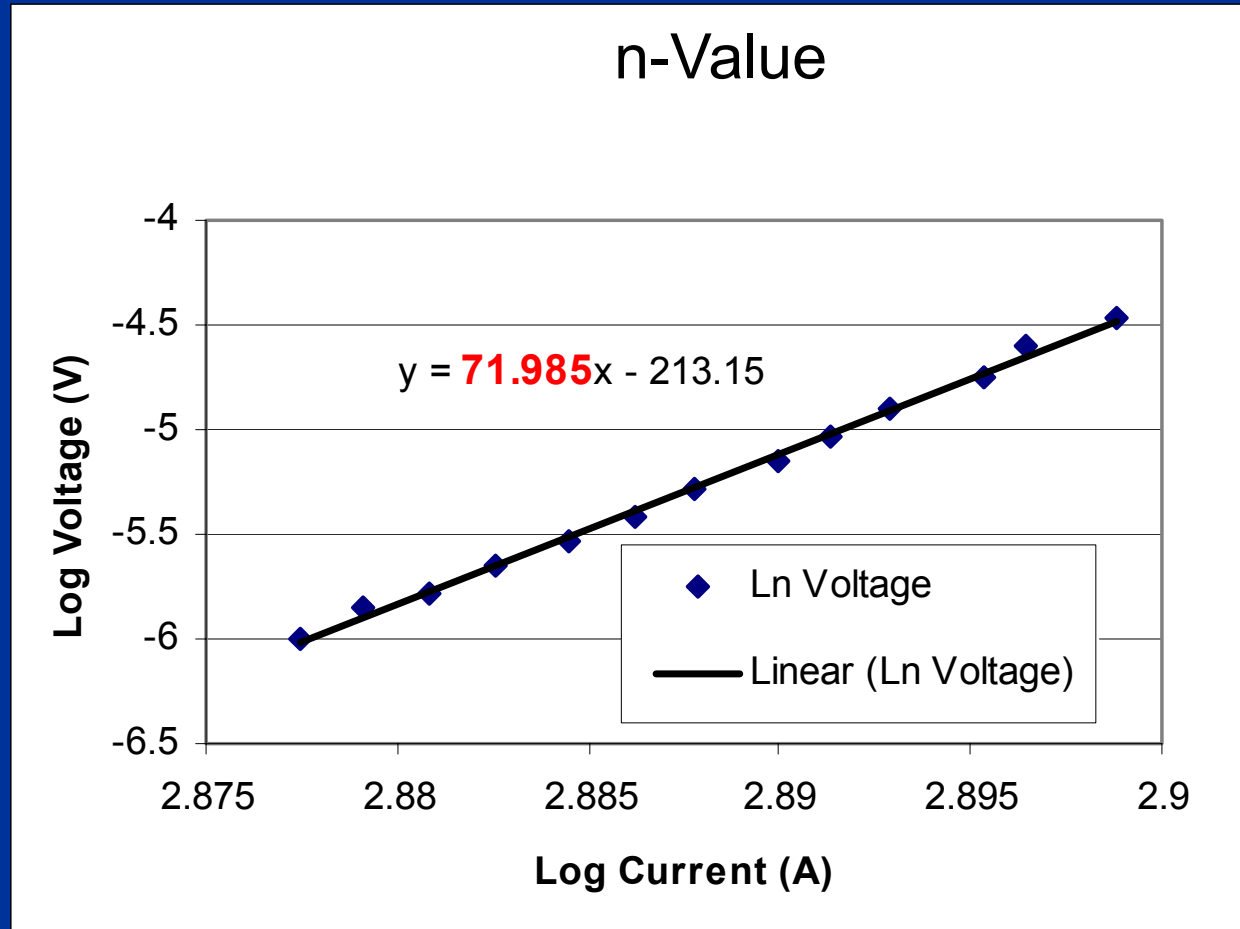Jc=2,900 A/mm^2 (0.819mm)

10^{-12} ohm-cm

- Most heat treatment studies have targeted 3000 A/mm^2
  $\rightarrow$ For lower J_c rod process wire we make, we have studied heat treatment to optimize both RRR and J_c

- For lower J_c material (1700 A/mm^2) it is possible to improve RRR with J_c loss of only a few%

  $\rightarrow$ Plan to do a similar study for e.g. 0.8 mm high J_c wire and see if a good balance between J_c and RRR can be consistently achieved
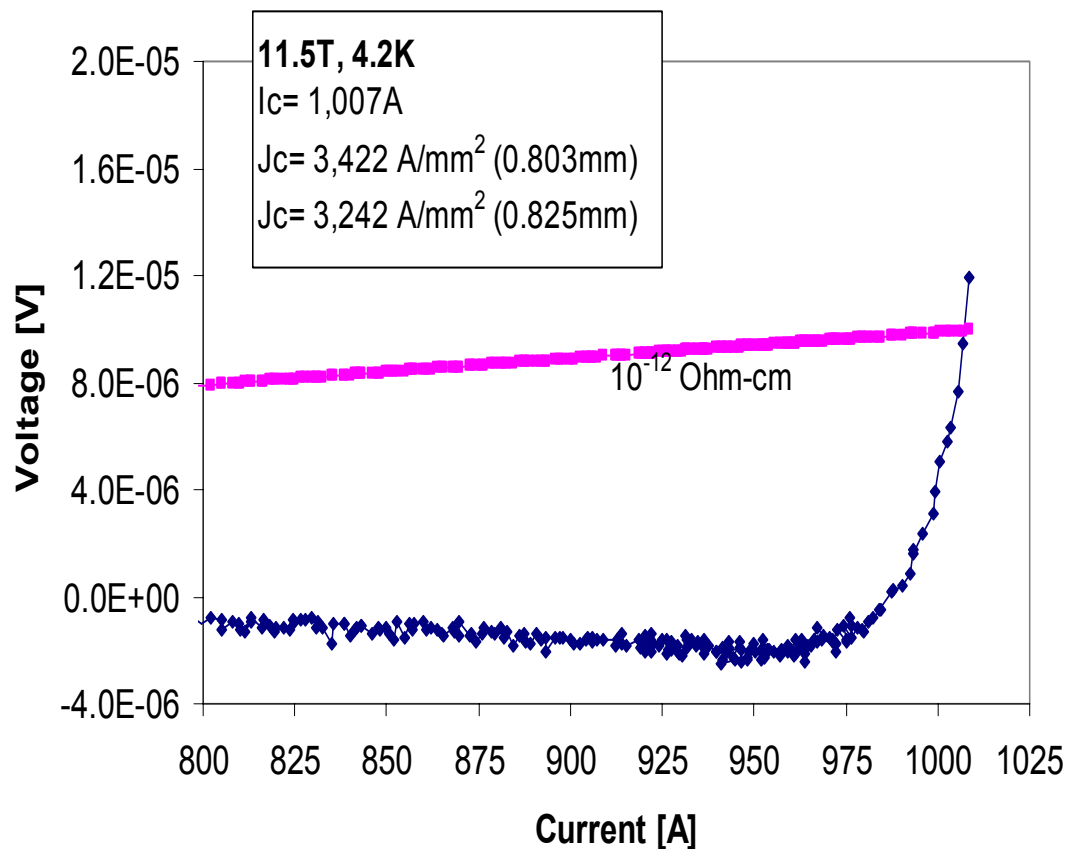

0.5 mm wire

S-2000 spec

RRR

HT hours at 695°C
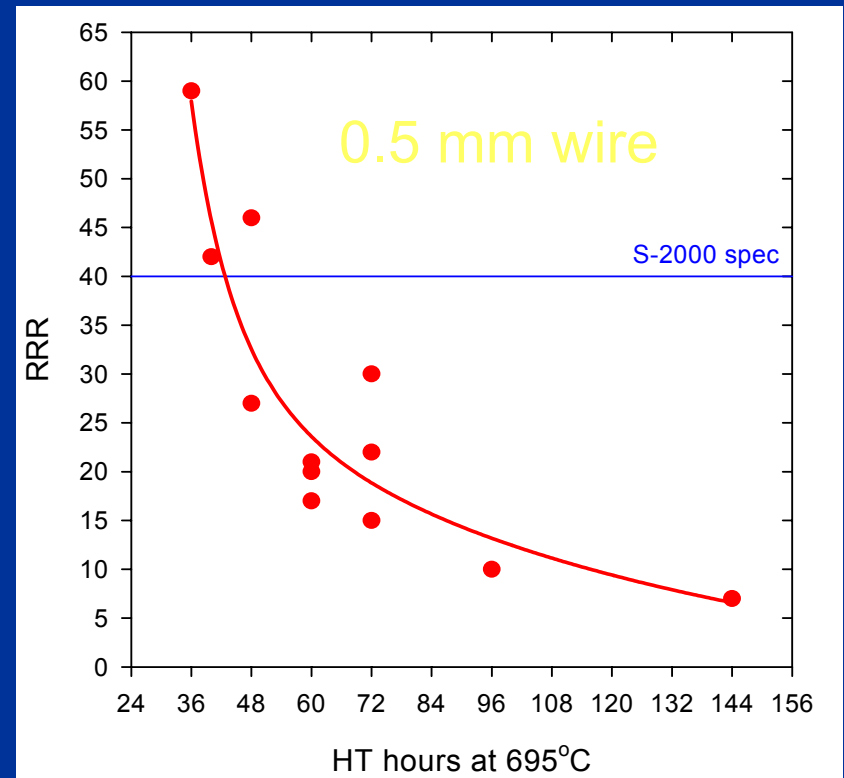
OST RRP--excellent Jc and n-values, with good RRR (15)

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RRP 6445 (650°C/200h)

11.5T, 4.2K
Ic= 1,007A
Jc= 3,422 A/mm^2 (0.803mm)
Jc= 3,242 A/mm^2 (0.825mm)

10^{-12} Ohm-cm

6445 (L38) 11T no/SF Joint Voltages

Both Joints + Sample
Top Joint
Bottom Joint

32.4 n-Ohms

$y = 3.24E-08x - 7.43E-05$
$y = 1.26E-08x - 7.30E-05$
$y = 1.44E-08x - 7.49E-05$
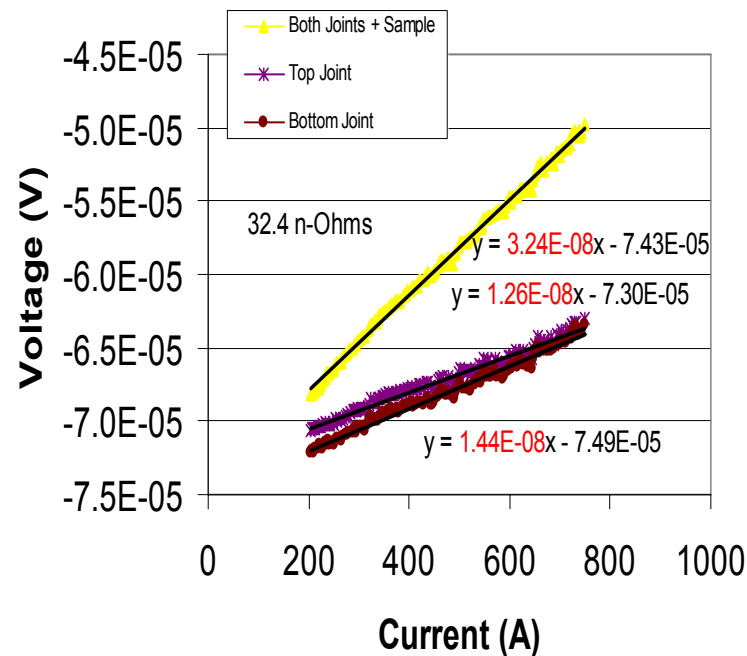
OI-ST 3000 A/mm² Strand: New J_{csc}

--From P. Lee, PAC'03

Legend:
- OI-ST 6445 RRP 0.9 mm (Parrell et al. ASC2002)
- OI-ST RRP 0.9 mm Kramer Extrapolation
- High J_c Internal Sn IGC EP2-1-3-2 700°C HT
- High J_c Internal Sn: ORe110(695/96)
- SMI-PIT Nb-Ta Tube: 64 hrs@675 °C-small grains
- High J_c Internal Sn MJR TWC1912
- 504 Filament SMI-PIT, small grains only
- ITER: Mitsubishi Internal Sn
- ITER: LMI Internal Sn
- ITER: Furukawa Bronze Process
- ITER: VAC 7.5% Ta Bronze Process

X-axis: Applied Field, T
Y-axis: Layer Critical Current Density, A/mm²

Non-Cu:A15 ratio from image analysis of high resolution FESEM images of 4 sub-elements

OI-ST RRP 3000 A/mm² (12T, 4.2K)
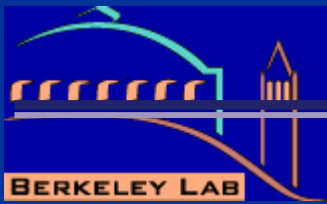
OST has completed production quantities of high Jc wires for use in HD-1

- MJR process (50 kg delivered Aug 2002, meets specification)

  --Jc (12T, 4.2K) > 2250 A/mm^2

  --RRR(copper residual resistivity ratio) > 2

  --Yield: > 72 % piece lengths > 250 m

  --D_{eff} < 120 microns

- RRP process (50 kg delivered Jan 2003, exceeds Jc spec.)

  --Jc > 2750 A/mm^2; best value > 3000 A/mm^2

  --RRR > 13

  --Yield: 86 % piece lengths > 250 m

  --D_{eff} < 120 microns

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HEP Conductor Inventory order status

- OST RRP ordered Oct, 2002--50 kg, complete July 2003

- OST RRP ordered July 2003--100 kg for delivery in Jan 2004

- OKAS order Jan 2002--150 kg. 12 kg delivered April 2003. Remainder of billets did not meet spec. and order canceled July 2003

- Demonstrate HER process for making high J_c wire
- Distributed barrier design (highest J_c, good D_{eff})
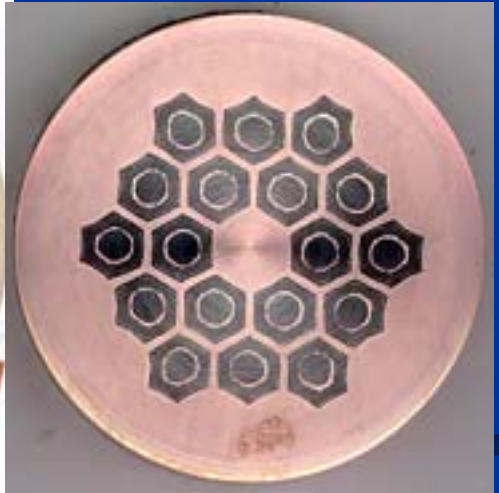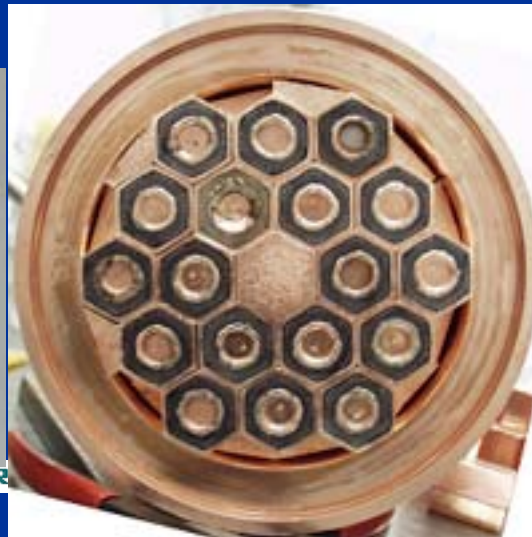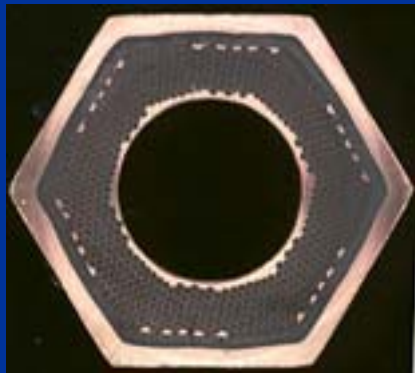- Cost reduction
- Improved RRR

4 tasks this year:

1) Distributed barrier, HER billet made with Nb-Ta components
   Goal: demonstration of DBHER process, highest J_c target
2) DBHER with Nb filaments and barrier, with Nb-47%Ti filaments
   Goal: reduced cost strand, more common alloys
3) Single extrusion method for incorporating Ta barriers into a DBHER wire
   Goal: improving RRR in a high J_c distributed barrier strand
4) Investigating new candidate materials for use as barriers for RRR improvement
   Goal: reduced cost, improved ease of fabrication high RRR strand

High J$_c$ DBHER demonstration billet (OST)

- Goal is high J$_c$, **D**istributed **B**arrier wire made with the **H**ot **E**xtruded **R**od process.
- Subelement design is same as used for high J$_c$ cold restacks (i.e. should be like rod process or MJR wire)
- Last year, we tried using Cu-Sn matrix, wire broke up at large diameter
- Challenge is to demonstrate ~3000 A/mm^2 wire made entirely by extrusion
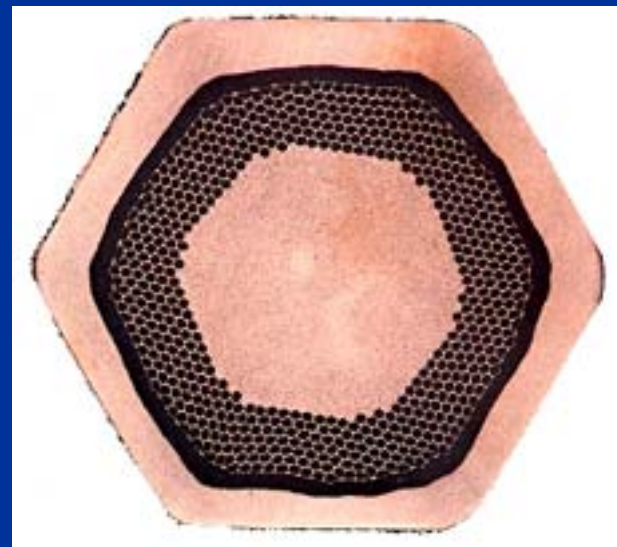
8-05-03

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Stacked billet
LAR ~0.2

After extrusion
2" diameter

Hex 1.023" FTF
Ready for
drilling hole to
receive salt

Alt. Ti source: mix Nb-47Ti rods into stack

➢ Substitute Nb-47wt%Ti rods for some Nb rods

➢ Nb-47wt%Ti hexes are readily available

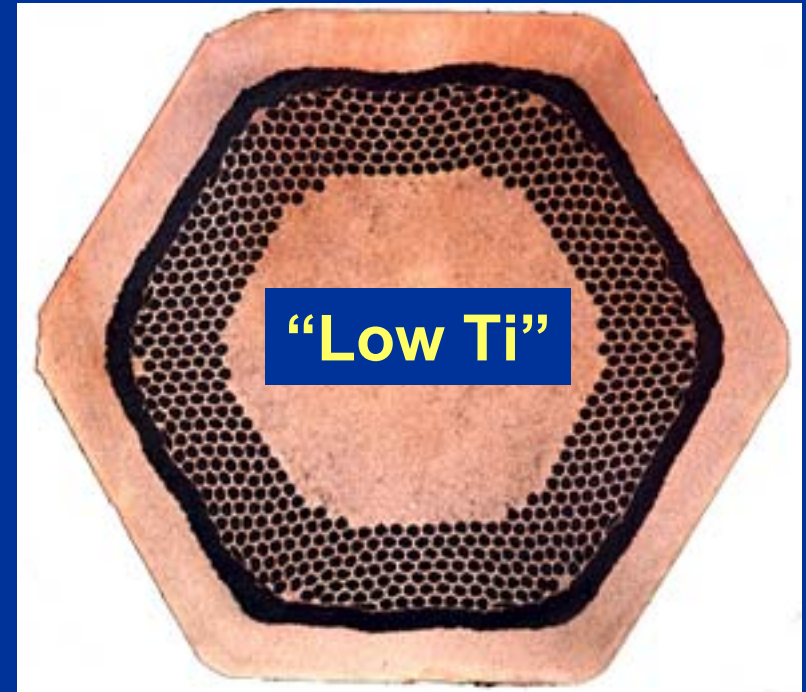➢ Goal is to eliminate the need for expensive (and less ductile) Nb-7.5%Ta and Sn-Ti alloys

Nb-47Ti filaments

Nb barrier

Sn core

Cu matrix

Nb filaments
LAR ~0.3
(reduced risk)

Superconducting Magnet Program
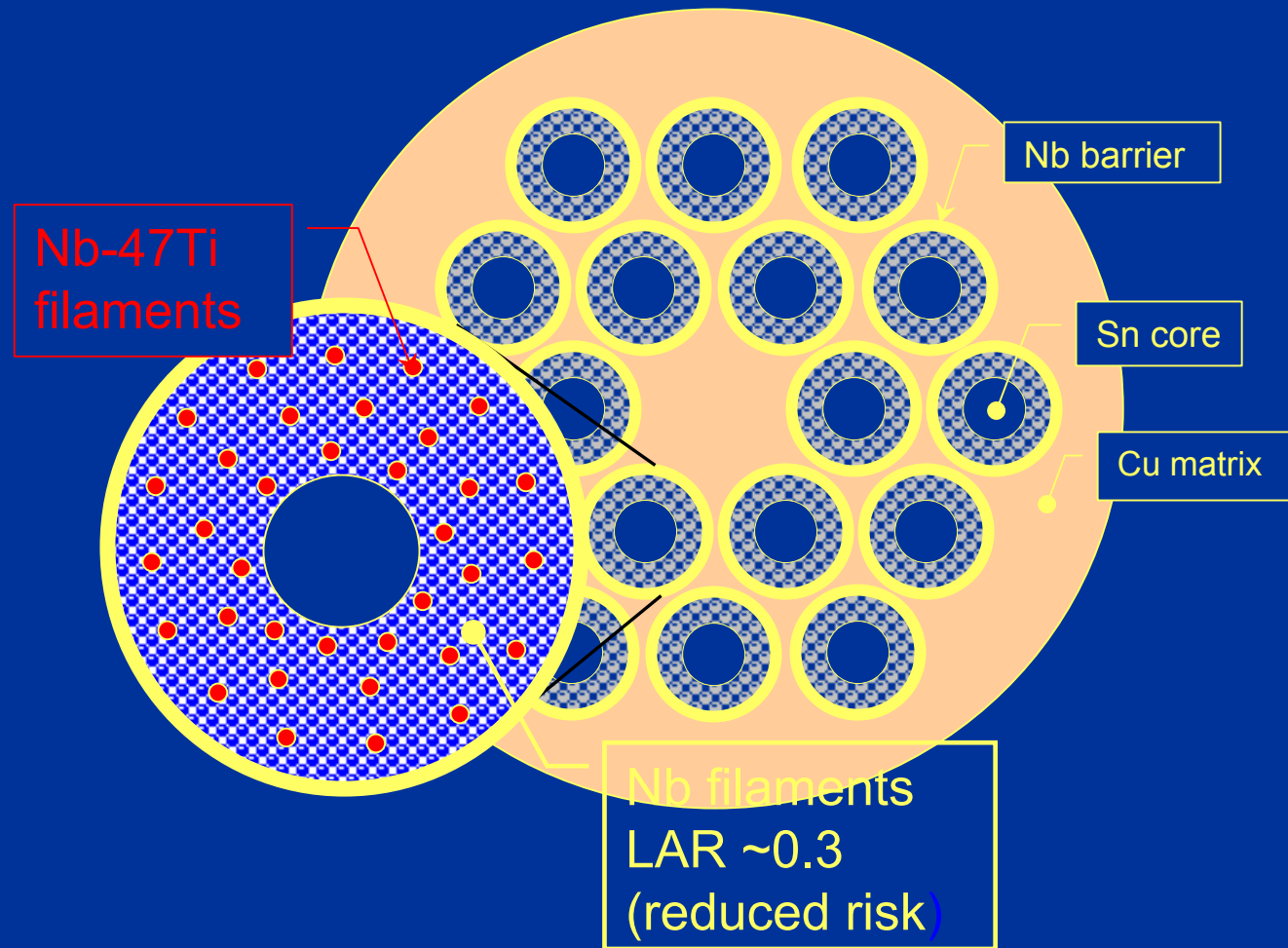
Status: alternative Ti source project

"High Ti"

"Low Ti"

After extrusion 2" diameter
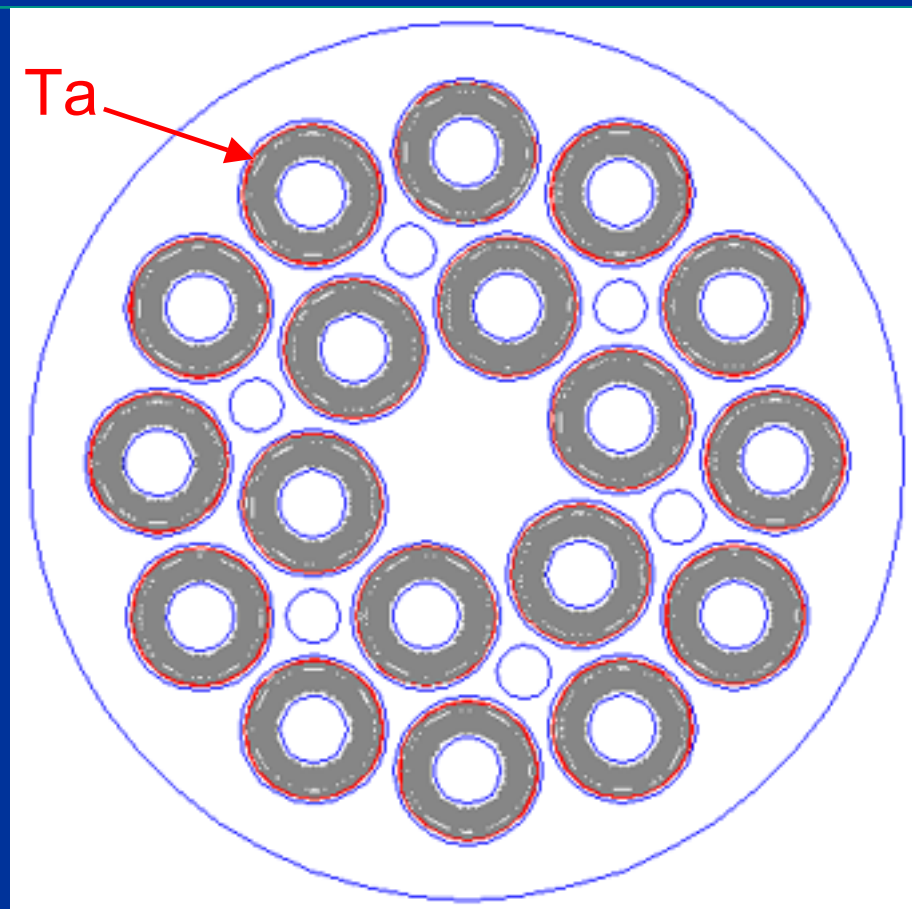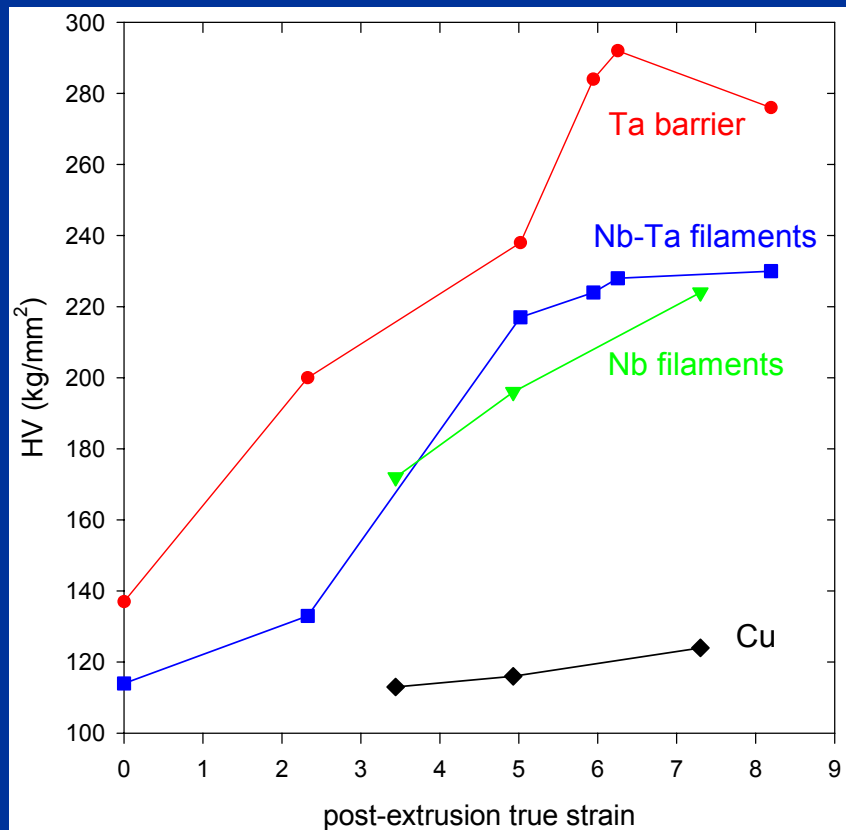
Hex 1.023" FTF
Ready for drilling
hole to receive salt

8-05-03

Superconducting Magnet Program

Single extrusion method for incorporating Ta barriers into a DBHER wire (OST)

> ➤ Ta work hardens too much to double extrude
> ➤ Use Ta, but only in single extrusion

What's next?--reduce D_{eff}

- Increase number of subelements

- Use fins to subdivide subelements

- PIT conductor fabrication

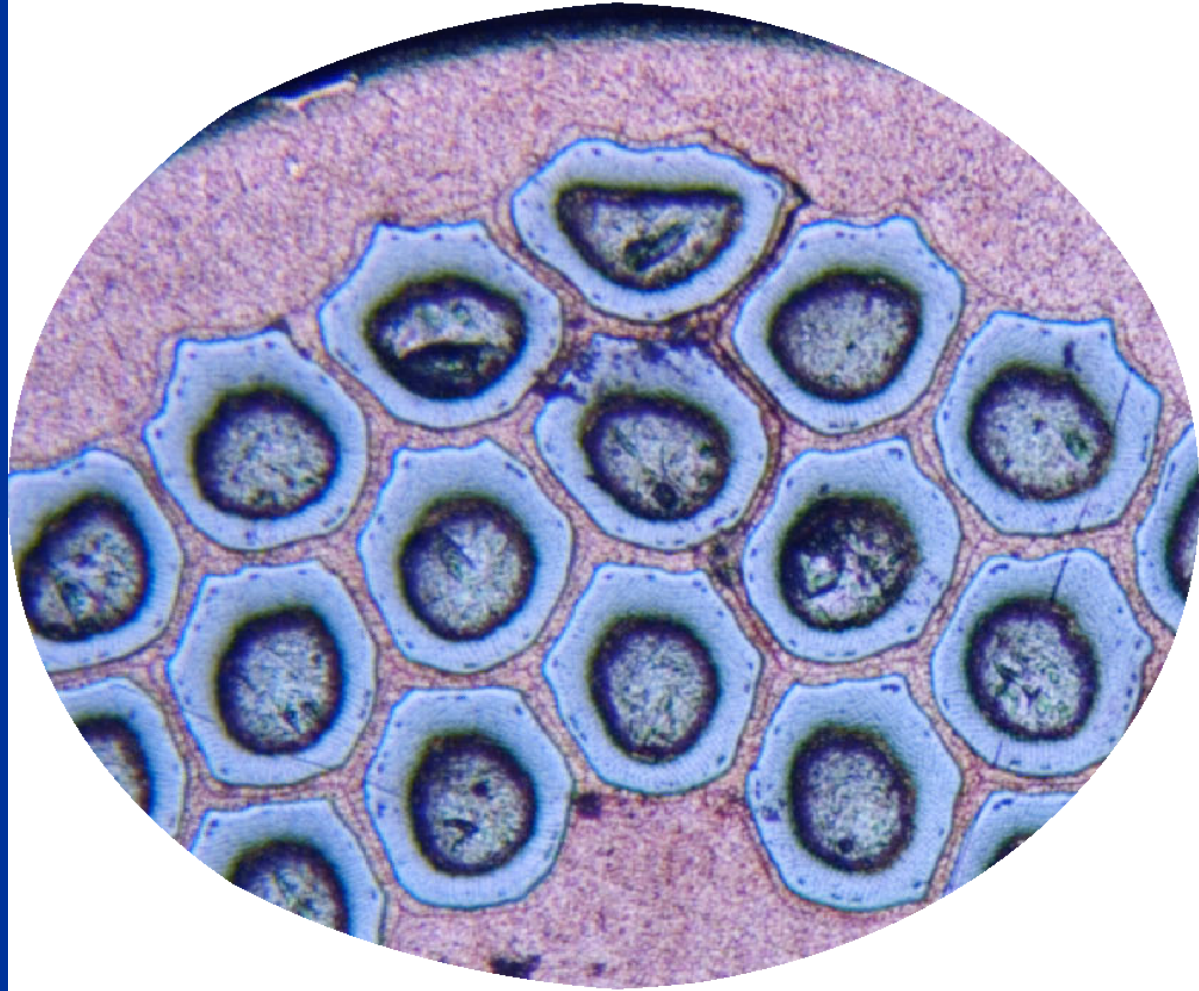**Subelement restack issues include:**

--**Single or double restack**

--**Bonding**

--**Subelement/barrier distortion**

--**Matching hardness of components**

OST RRP--54 subelements
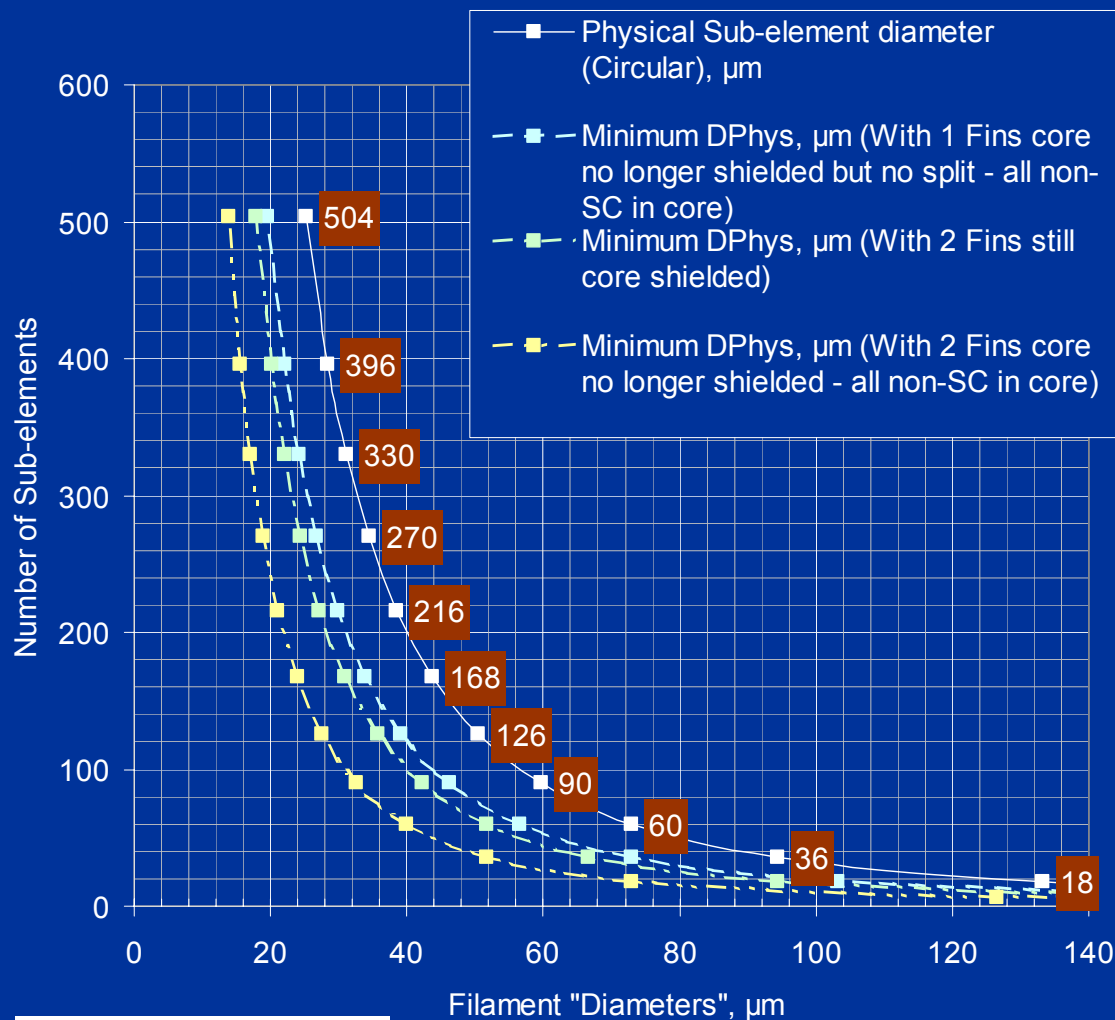
More Sub-Elements Required . . or

- Large number of sub-elements needed – with associated stacking problems – unless the subelements are sub-divided

- Even so, > 36 subelements required

From P. Lee, PAC'03

Legend:
- Physical Sub-element diameter (Circular), μm
- Minimum DPhys, μm (With 1 Fins core no longer shielded but no split - all non-SC in core)
- Minimum DPhys, μm (With 2 Fins still core shielded)
- Minimum DPhys, μm (With 2 Fins core no longer shielded - all non-SC in core)

X-axis: Filament "Diameters", μm
Y-axis: Number of Sub-elements

Data labels: 504, 396, 330, 270, 216, 168, 126, 90, 60, 36, 18

- SBIR work by Supergenics/OKAS

  --Ta 40 wt% Nb alloy

  --radial fins to prevent filaments from coalescing

  --short barrier section to prevent reaction on Nb barrier

  --add more fins to further subdivide Nb_3Sn

  --penalty is only 0.8 % area fraction per fin

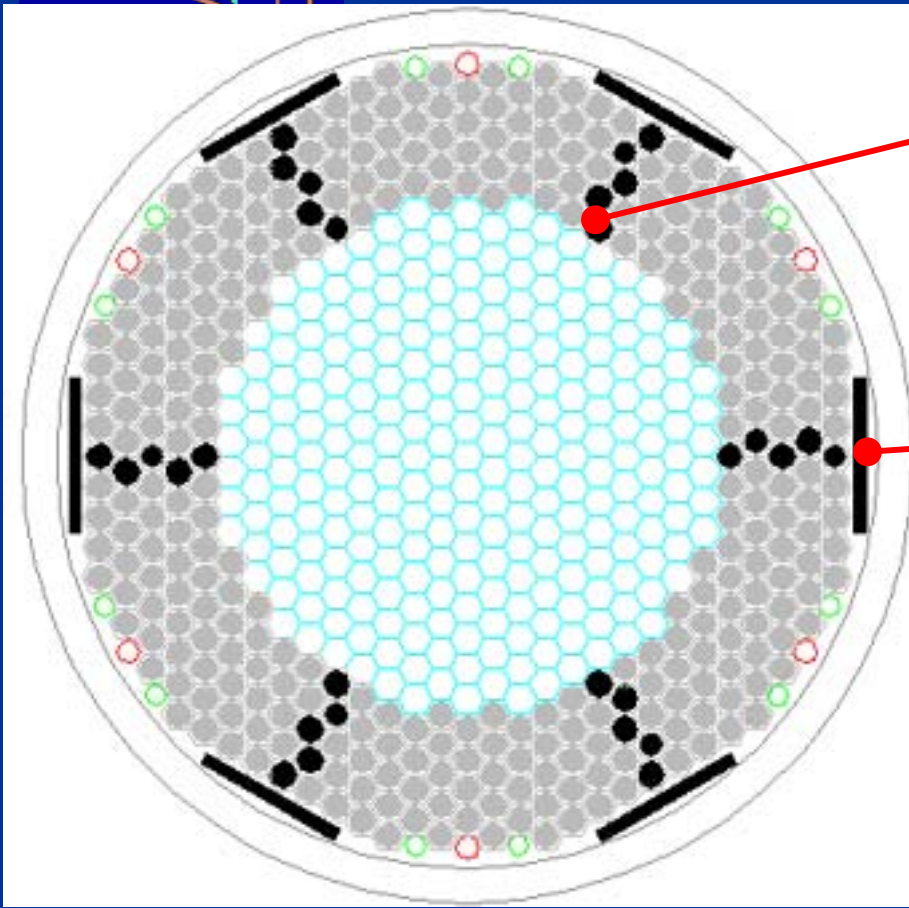- Should be applicable to many fabrication processes

8-05-03
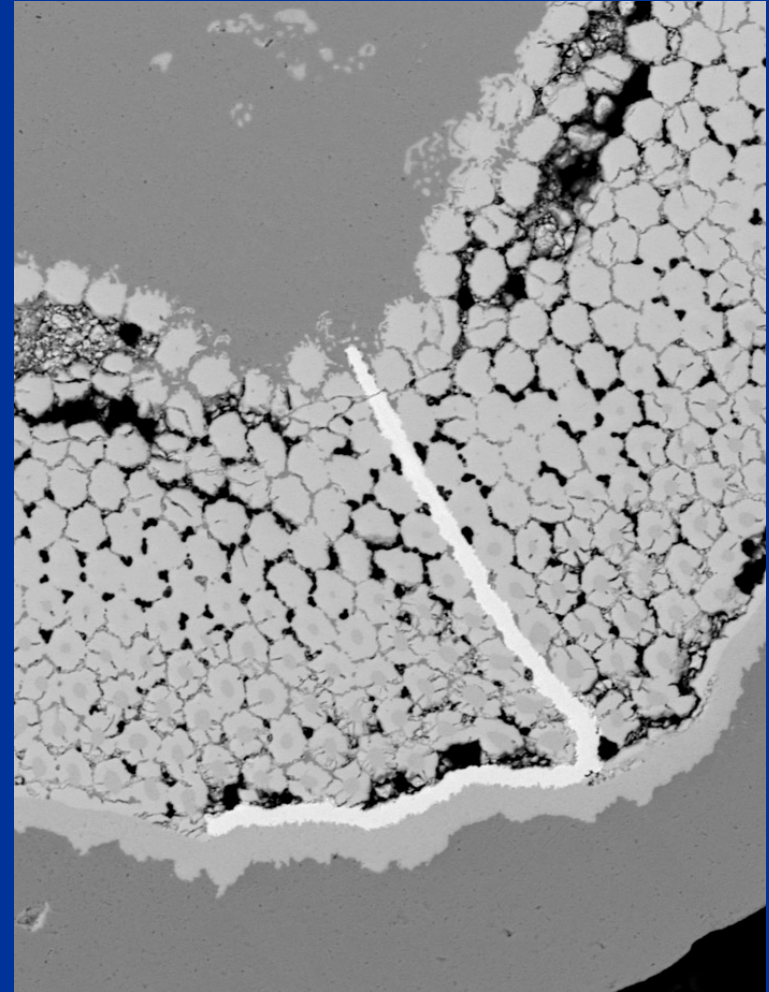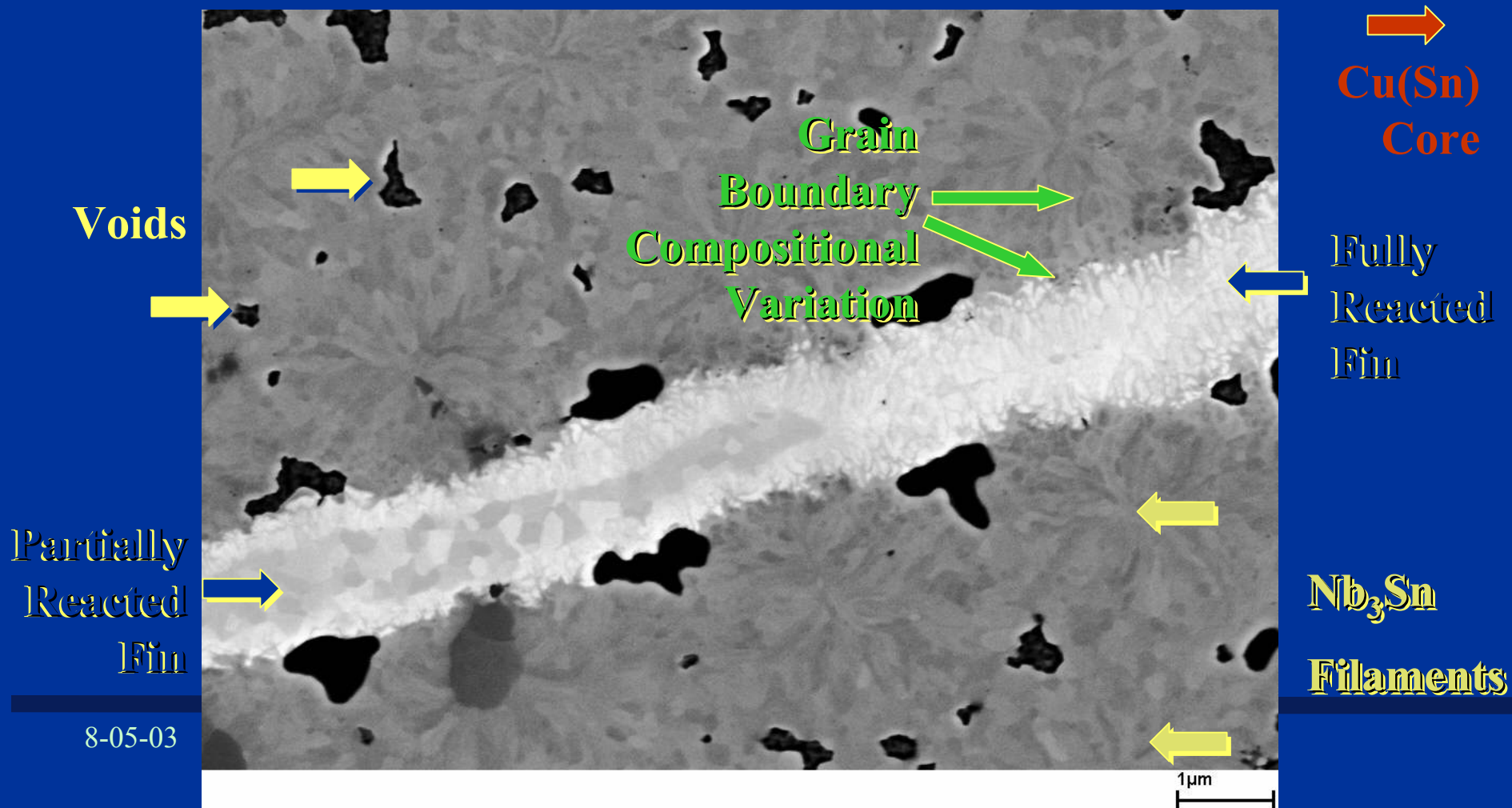
Reduced D_{eff} subelement(OST)

Annealed Ta (or Ta-Nb) wires packed in stack to make dividers (could be Cu clad)

Annealed Ta (or Ta-Nb) sheet placed against barrier to prevent Nb_3Sn formation on Nb tube

Use annealed Ta inserted before subelement extrusion to make best use of available Ta ductility/strain space
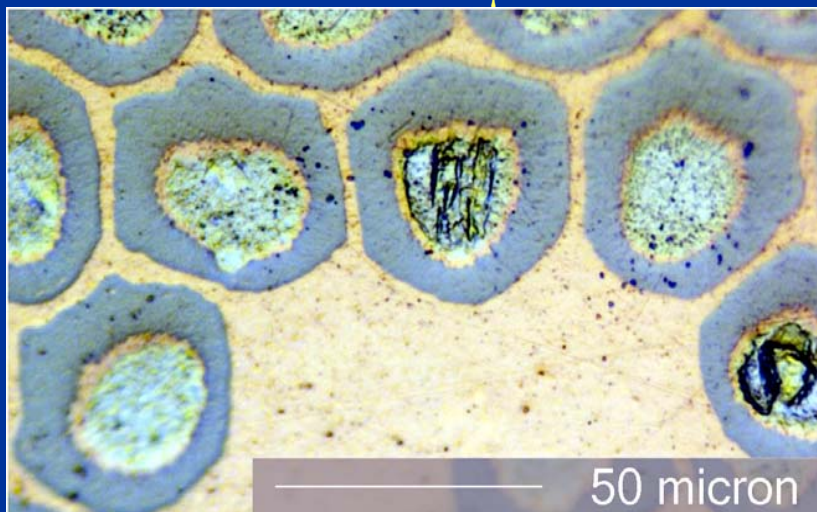
Effective filament size could be reduced to $\leq 40\ \mu m$ for 0.8 mm, 37 stack DBHER

BERKELEY LAB

Decrease D_{eff} by putting more bundles in restack(OST)

- Straightforward method to reduce D_{eff}
- Restack having >100 bundles possible for cold restacks, not DBHER process (37 is limit, would have to use split subelement)
- Experiments with 61-stack strand show potential problems w/ subelement sizes <50 μm

Wire diameter	Subelement size		
	37 stack	61 stack	127 stack
1.0 mm	128 μm	100 μm	69 μm
0.8 mm	103 μm	80 μm	56 μm
0.6 mm	77 μm	60 μm	42 μm
0.4 mm	51 μm	40 μm	28 μm

50 micron

? Will more bundles make deformation more uniform --less breakage?
? Is higher LAR required—reduced J_c but less breakage?
? What about keeping LAR ~0.2 but increasing filament size-copper web thickness?

*Superconducting Magnet Program*

❑ **If 19-stacks this year are success, extending process to 37-stack would be next step:**

- Reduced D_{eff}
- Reduced effect of break in any one subelement in cross section
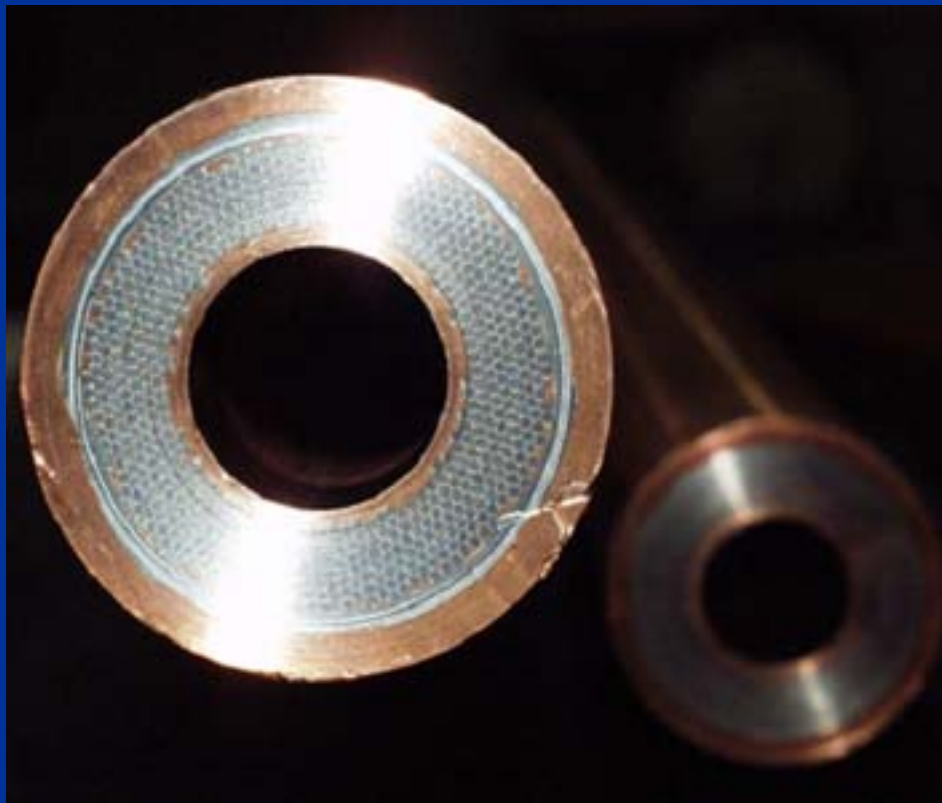- More uniformly shaped subelements in final wire

❑ **Would require:**

- Larger restack billet diameter
- Extruding rod to larger size to keep salt holes large enough for Sn insertion
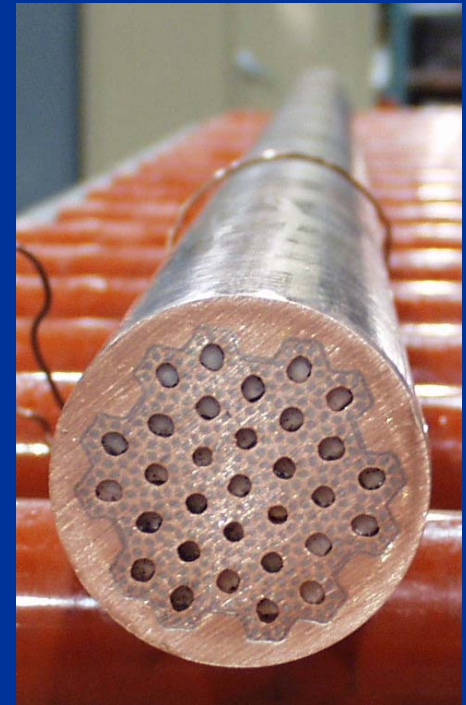
➢ Subelement extruded to tube could be used for cold restacks or DBHER billets

• Present process is extrusion of solid rod having copper center

• Hole for Sn is gundrilled into core
• Length of rod limited to several feet
• Elimination of drilling stage could allow rod of many feet
• Improved cycle time

8-05-03

- Task I

  Fabrication of Optimized Billet Design

- Task II

  Fabrication of Billet with Nb1wt%Zr

- Task III

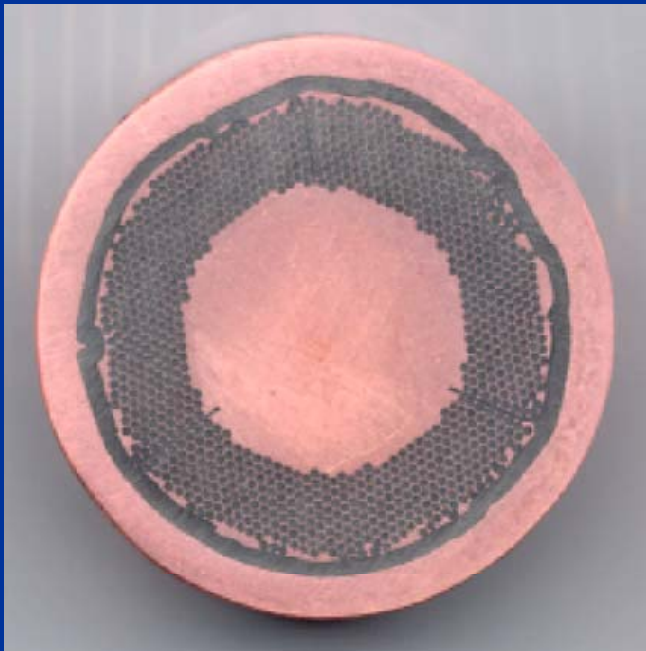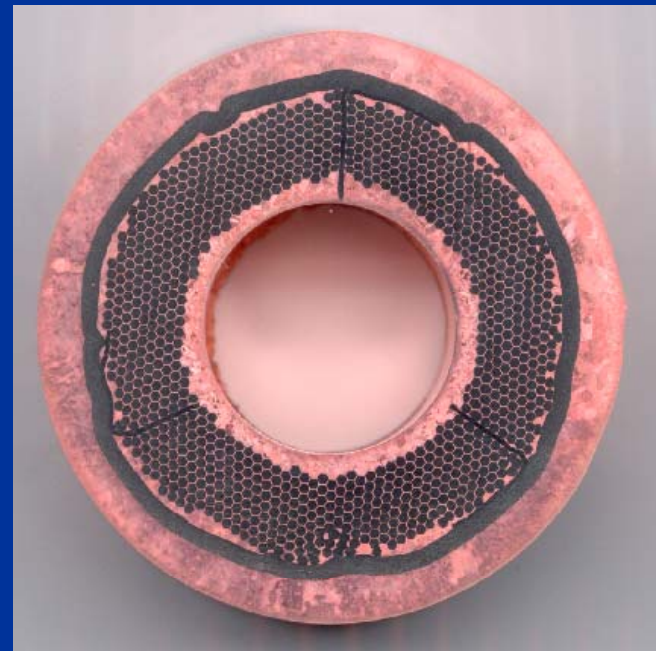 Investigation of an alternative method of introducing Ti into the Nb_3Sn phase

- To fabricate 7"x 12" billet with Nb7.5Ta

- Thicker Nb individual barrier

- Sub-divided subelement with three TaNb internal separators to reduce D_{eff}

Billet TP-8 with 3 Separators

Extruded

Drilled

- Billet with three fins extruded successfully

- Two different Sn sources used
  (SnTi & SnCu)

- Monocore element drawn to 0.15 mm without breaks

- Drawing problems with 19 subelement restack wire at 5 mm diam.

Individual Barrier and Separator:

- Based on the performance of billet TP-8, optimize the thickness of barrier and number of separators.

- Apply TaNb alloy with various compositions to individual barrier.

- Nb/Ta double layered barrier (billet SP-1)

Improvement on Drawability:

- Rod-in-tube approach to mono process to minimize the work hardening of filaments
- Maintain the possible maximum LAR of Nb/Cu by adjusting the size of Cu tubing
- Employ Nb7.5Ta with SnCu alloy to avoid an effect of Ti precipitate in SnTi compound

Nb1wt%Zr:

Apply Lowest Possible Extr Temp with 7"
    billet To Utilize the Max Press Capacity

Strengthen the Outer Jacket (Glidcop, CuNi)
    To Reduce the Differential Flow Stress

Reduce the Extrusion Reduction Ratio
    To minimize the Adiabatic Effect

Co-Extrude with Internal Barrier

Steady progress continues toward program coals

- **Long Range Goals**

  - $Jc = 3000$ A/mm^2

  - D_{eff} = 40 microns or less

  - Piece length > 10,000 m

  - Heat treatment < 400 hr

  - Cost: < $1.50/kA-m(12 T)

- **Progress**

  - $Jc = 3000$ A/mm^2 (FY03)

  - Proof of principle shown; practical demos in progress

  - 250-1500m for both MJR and RRP internal Sn processes

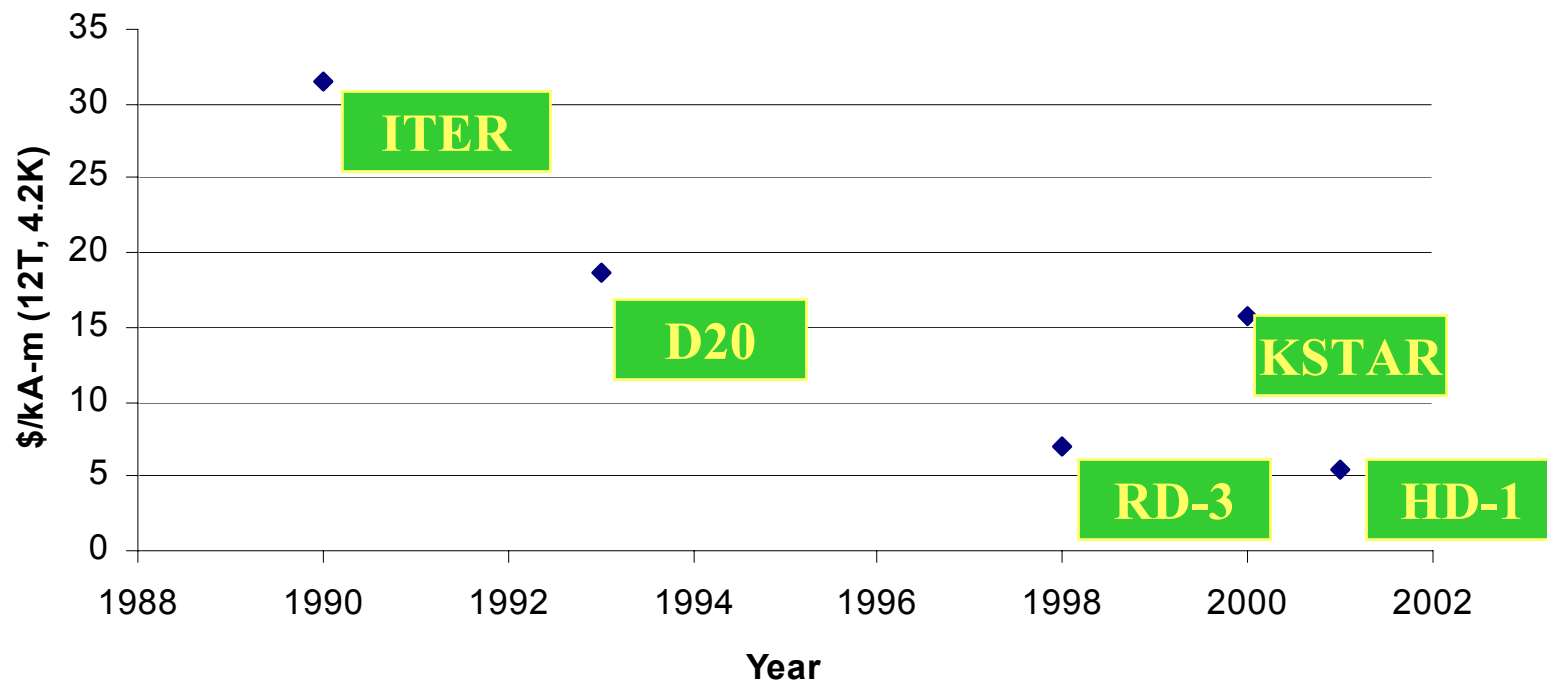 - 150 hr

  - $ 5.50/kA-m (Int. Sn)

    $7.75/kA-m (MJR)

- Nb$_3$Sn (OST RRP)--$5.75/kA-m

- Nb$_3$Sn (MJR)--$7.74/kA-m

- Nb$_3$Sn (PIT)--$28.94/kA-m

- Bi-2212 (PIT)--$57.00/kA-m

These prices are for small, custom-processed orders

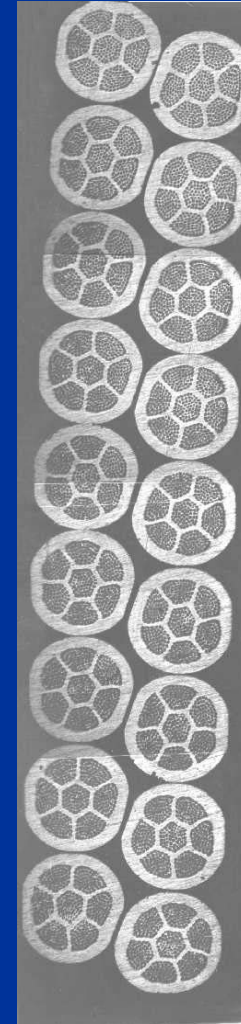# Cost/performance improvements for HEP and Fusion-type Nb_3Sn wires

Further improvements must come from process scale-up. New ITER?

Superconducting Magnet Program

Bi-2212 round wire shows promise for accelerator magnets

- Jc(12T, 4.2K, non-silver) > 2000 A/mm^2 in new material (Showa)

- Long lengths(> 1500 m) are being produced

- New result: 30 strand cable; Ic = 6.8 kA at 6 T

- React/wind (BNL) and Wind/react (LBNL) coils are being made

Cable made at LBNL

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